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12 PERSONAL AUTHOR(S) Paul R. Krehbiel and Grant Gray

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The New Mexico Tech Wideband/Coherent Radar was shipped by rail to Kennedy Space Center on 17 July 1991. A problem in the transmitter cooling system delayed full operation until mid August. Electrification signatures were first observed on 15 September and numerous cases were documented between then and tear-down on 6 October. In addition, several cases of coordinated dual-Doppler and tomographic data were acquired in conjunction with the NCAR CP2 radar. Preliminary results have been presented in papers and conferences. After its return to New Mexico, several upgrades were made to the transmitter to increase reliability.

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Third Year Interim Report for AFOSR Grant AFOSR-89-0450
"Remote Sensing of Precipitation and Electrification with a
Dual-Polarization, Coherent, Wideband Radar System"
July 15, 1991 to July 15, 1992

The first year's research provided preliminary indications that a dual-polarization radar could detect extensive regions of particle alignment in electrified clouds. It was also verified, as anticipated in the proposal, that lightning echoes are detectable by 3 cm. radar by observing the cross-polar return.

During the second year of the contract extensive upgrades to the receiver chain for the radar were made. Real-time signal processing and display systems were added to the system to supplement the existing time-series recording system, and to give radar operators timely operational information so as to better manage instrumentation resources during an experiment. Completion of the modifications was targeted for June, 1991, so that the system could be part of the Convective and Precipitation Experiment (CaPE) at Kennedy Space Center (KSC), Florida, during July/August of 1991.

Our objectives for the KSC effort were to a) complete and test the upgraded radar and the real-time processing/display system, and b) follow up on the work done by Hendry and McCormick on particle alignment in electrified storms. Hendry and McCormick had suggested that the correlation coefficient between the co- and cross-polar received signals could be used to identify regions of strongly aligned cloud partices. Of particular interest were regions above the freezing level where ice particles align with a strong electric field.

On July 17, 1991, the radar was shipped via rail to KSC. Prior to shipment Paul Krehbiel and Grant Gray had been to KSC,and had picked a site near the Shuttle Landing Facility (SLF) for the NM Tech radar operations. The site was near a 5 cm tracking radar operated for NASA by Lockheed. The NCAR CP2 radar was located 18 km NNW of the Tech radar and in good position for coordinated multipolarization studies and dual Doppler measurements. The NM Tech radar was in place July 29 and we were ready to begin initial testing.

During setup a coolant line fault resulted in damage to the transmitter final amplifier tube. The manufacturer, Hughes, quickly repaired the tube and returned it to us at KSC. In the meantime we continued work on the DSP and display software. The radar was back in operation on 17 August.

After over two weeks of dry weather, we finally saw some precipitation echos, but with little associated electrical activity. Toward mid-September we were fortunate to begin seeing cases of strongly electrified storms within radar range. On September 15, after working out some bugs in the correlation code, we saw our first electrification signature. Increasing values of cross-polar correlation above the freezing level were observed, as predicted. Though we expected to see decreases in correlation following lightning discharges, we were surprised that the effect would be so dramatically apparent on the color-enhanced radar display. This afforded solid evidence not only that the description of the alignment effect was accurate, but that the radar was working quite well, with excellent isolation between the orthogonal polarizations. Using the correlation/phase display, NM Tech radar operators and visitors alike quickly became skilled at predicting within a few seconds the occurrence of lightning strikes. KSC personnel expressed interest in the technique as a means to reduce costly delays incurred in transporting electrostatic-sensitive rocket components between sites during electrical storms.

With the radar operating in circular polarization mode we were able to use the phase of the complex cross-polar correlation to determine changes in the angle of orientation of ice particles. In many instances we observed slow shifts in phase leading up to a discharge, with sudden large phase shifts immediately following the discharge, indicating rotation of the particles with the electric field changes. In many cases, change in correlation phase was as dramatic an indicator of elecrification condition as was the correlation amplitude change.

The CaPE project terminated operations on August 19, but plans had been made by NM Tech to continue independent measurements and to make coordinated measurements with NCAR's CP2 between August 19 and October 1. Several cases of dual Doppler and tomographic data (storms directly between the the NM Tech and CP2 radars) were recorded during the period from 19 August to 1 October.

Following shutdown of CP2 operations, two days were spent acquiring both raw and processed sea clutter data. The NM Tech radar was disassembled and readied for rail shipment back to Socorro during October 6-10.

Upon returning to Socorro, Gray and Chen began writing software for radar data perusal, cataloging, and analysis. Krehbiel, Gray, Rison, and Chen prepared and delivered a presentation on the cross-polar correlation technique at the 1991 Fall AGU meeting in San Francisco. In June, 1992, Krehbiel delivered a presentation to the Ninth International Conference on Atmospheric Electricity in St. Petersburg, Russia. Also in June, Blackman presented results at the URSI Commision F Open Symposium at Ravenscar, UK.

The radar finally returned by rail in late December. During January '92 it was reassembled in the NM Tech Workman Center compound. The radar transmitter's aging grid modulator had become unreliable. McCrary and Gray designed and constructed a smaller, more robust replacement using modern components. During June and early July of 1992, the radar was prepared to gather data coordinated with the Langmuir Lab lightning studies later in the summer.

Graduate Students: One graduate student, Mr. Tiehan Chen, was supported by this grant during the third year. Mr. Chen refined the data acquisition and display code for the radar, and is now engaged in detailed analyses of selected storm cases. His work and support will continue during the next year.

Publications/Presentations: The following presentations and papers have resulted from the third year's work on this grant:

Krehbiel, P., T. Chen, S. McCrary, W. Rison, G. Gray, T. Blackman, M. Brook. December, 1991. Presentation: American Geophysical Union, Fall Meeting. San Francisco.

Krehbiel, P., T. Chen, S. McCrary, W. Rison, G. Gray, T. Blackman, M. Brook. June, 1992. *Proceedings: Ninth International Conf. on Atmospheric Electricity.* St. Petersburg, Russia. pp 166-169.

Krehbiel, P., T. Chen, S. McCrary, W. Rison, G. Gray, T. Blackman, M. Brook. June, 1992. Presentation: URSI Commission F Open Symposium. Ravenscar, UK.

Copies of the above papers and abstracts are attached.

Ninth International Conference on Atmospheric Electricity, St. Petersburg, Russia, June, 1992.

Dual-Polarization Radar Signatures of the Potential for Lightning in Electrified Storms

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Abstract. *Real-time correlation and display of the co-polar and cross-polar radar returns from electrically active storms has provided dramatic indications of the buildup of electric stress in the storms, and of its collapse at the time of lightning. Following up on the pioneering work of Hendry and McCormick, strong correlations are observed above the 0 °C level in the middle and upper parts of storms that are indicative of the presence of electrically aligned particles. Regions of strong correlation are readily identified in scanning a storm, and provide an excellent indicator of the potential for lightning in the storm. The correlation values have been used to predict the occurrence of individual lightning discharges in storms; in addition, they have been used to detect the onset of electrification and to tell when a storm is finished producing lightning.*

1. Introduction. In a pioneering study, Hendry and McCormick (1976) of the National Research Council in Canada reported radar observations which indicated that particles were being electrically aligned in the upper levels of thunderstorms. The observations were made using a dual-channel circular polarization radar which operated at 16.5 GHz, and were obtained by coherently correlating the co-polar (e.g. RHC) and cross-polar (LHC) returns from a storm. Large correlation coefficients, indicative of a high degree of common particle orientation, were observed in the upper parts of storms. The correlation values decreased at the time of lightning discharges and regenerated between discharges. Lightning was sometimes also observed to *increase* the correlation or alignment.

In this paper we describe dual-polarization observations which confirm and extend Hendry and McCormick's results. The observations were made at Kennedy Space Center, Florida, as part of the Convective and Precipitation/Electrification (CaPE) program conducted there during the summer of 1991.

2. Measurements. For the measurements of this study, the radar transmitted alternate pulses of right- and left-hand circular polarization, and simultaneously received the co-polar and cross-polar returns from each pulse. The receiver outputs were digitized, processed and displayed in real time. The processing was accomplished with PC-based digital signal processors and the results were displayed on a high resolution monitor of the host PC. The radar operated at 9.8 GHz (3 cm wavelength) with 20 kW peak transmitted power and utilized a circularly-symmetric Cassegrain antenna with a corregated feed to maximize polarization purity.

For detecting the presence of aligned particles, the simultaneous co- and cross-polar returns for a given transmitted polarization were coherently correlated to give the squared magnitude $|\rho|^2$ and phase ϕ of the correlation function. The various quantities were displayed in PPI and RHI format to show their structure as the radar scanned through a storm. Lightning occurrences were detected using an electric field change meter and a directional optical detector attached to the radar antenna.

3. Results. Figures 1a and 1b show vertical cross-sections of the various polarization variables in a storm on Day 278, 1991. (The scans do not extend down to ground level because radar transmissions at KSC were restricted at low elevation angles.) The two sets of cross-sections are from sequential scans just before and after an intracloud lightning discharge occurred in the storm, and were separated by less than 20 seconds in time. The figures show the co-polar and cross-polar reflectivity structure, the resulting circular depolarization ratio (CDR), and the squared magnitude and phase of the co-polar – cross-polar correlation. The storm was 15 to 27 km distant from the radar and extended up to 13 km altitude (MSL), with two cells being evident in the co-polar reflectivity.

In the scan just prior to the lightning (Figure 1a), two regions of strong correlation ($|\rho|^2 > 0.75$) ex-

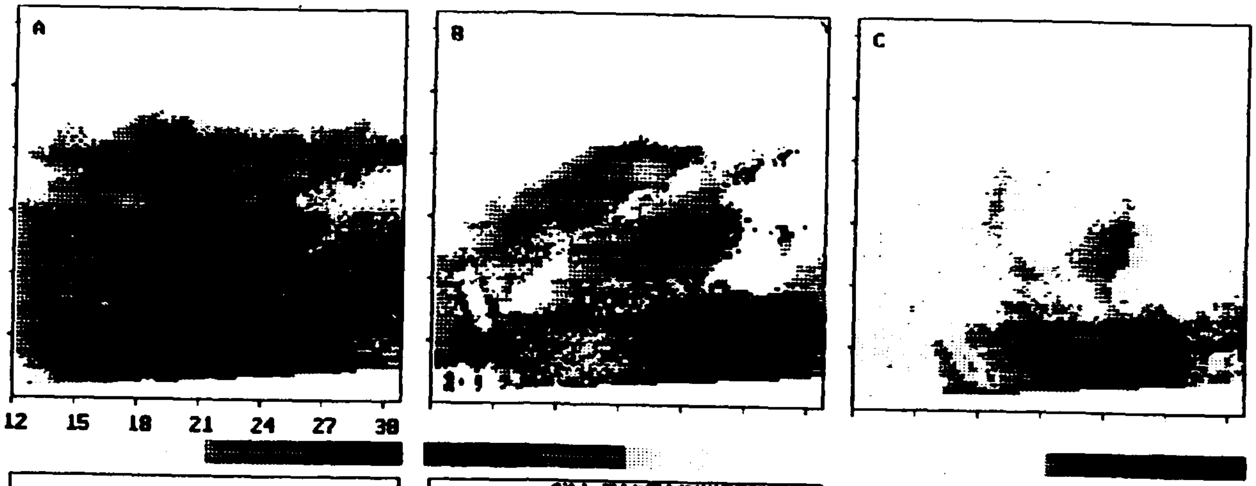

Figure 1a. Vertical cross-sections of *a*) co-polar reflectivity, *b*) circular depolarization ratio, *c*) cross-polar reflectivity, and the correlation quantities $|\rho|^2$ (d) and ϕ (e), just prior to a lightning discharge in the storm. The distance scale is 3 km per tic mark. Contours are at 20 dB intervals for reflectivity, 12 dB for CDR, 0.25/1.0 for $|\rho|^2$ and $\pi/2$ for ϕ.

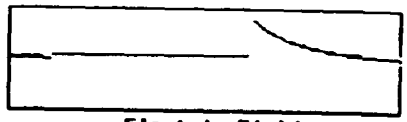

Figure 1b. Same as Figure 1a, except 20 seconds later, just after an intracloud discharge occurred in the storm. The electric field change of the discharge is shown above. Note disappearance of $|\rho|^2$ correlation regions.

isted at mid-levels (6-9 km MSL) in the far cell and in the upper part (9-12 km) of the near cell. These were associated with local maxima in the cross-polar reflectivity and CDR. After the discharge, the correlation regions had essentially disappeared and the associated cross-polar returns and CDR had diminished in intensity. The co-polar returns were unchanged in the two scans, as were the cross-polar returns and CDR values below the melting level, at about 4–4.5 km altitude.

Correlation regions such as described above were observed to regenerate gradually until the next discharge, which would wipe them out and restart the cycle. Figures 2a and 2b show how the polarization quantities varied with time at a fixed location in the electrically active region of two storms. Each figure shows 5 minutes of data and includes the electric field change record of lightning occurrences. The data of Figure 2a are from 8.7 km altitude in a storm where lightning occurred at nearly regular time intervals; each discharge was accompanied by sudden decreases in both the cross-polar power and the correlation magnitude, as well as by rapid phase excursions. Figure 2b shows more complex behavior at 10.4 km altitude in another storm system in which the lightning activity was irregular and superimposed on activity from other storms. In one instance near the beginning of the Figure 2b data, the correlation increased at the time of lightning.

4. Discussion. Regions of strong co-polar – cross-polar correlation are readily identified in scanning through a storm and appear always to be present in electrified storms. As noted by Hendry and McCormick (1976), the fact that the correlation values are affected by lightning and are observed above the 0 °C level indicates that they are caused by the electrical alignment of ice particles, presumably crystals. The effect of alignment upon the correlation is suprisingly strong, and produces 'signatures' as in Figure 1a which are found to be an excellent indicator of the potential for lightning in a storm. We have been able to predict the occurrence of numerous discharges from the real-time correlation observations.

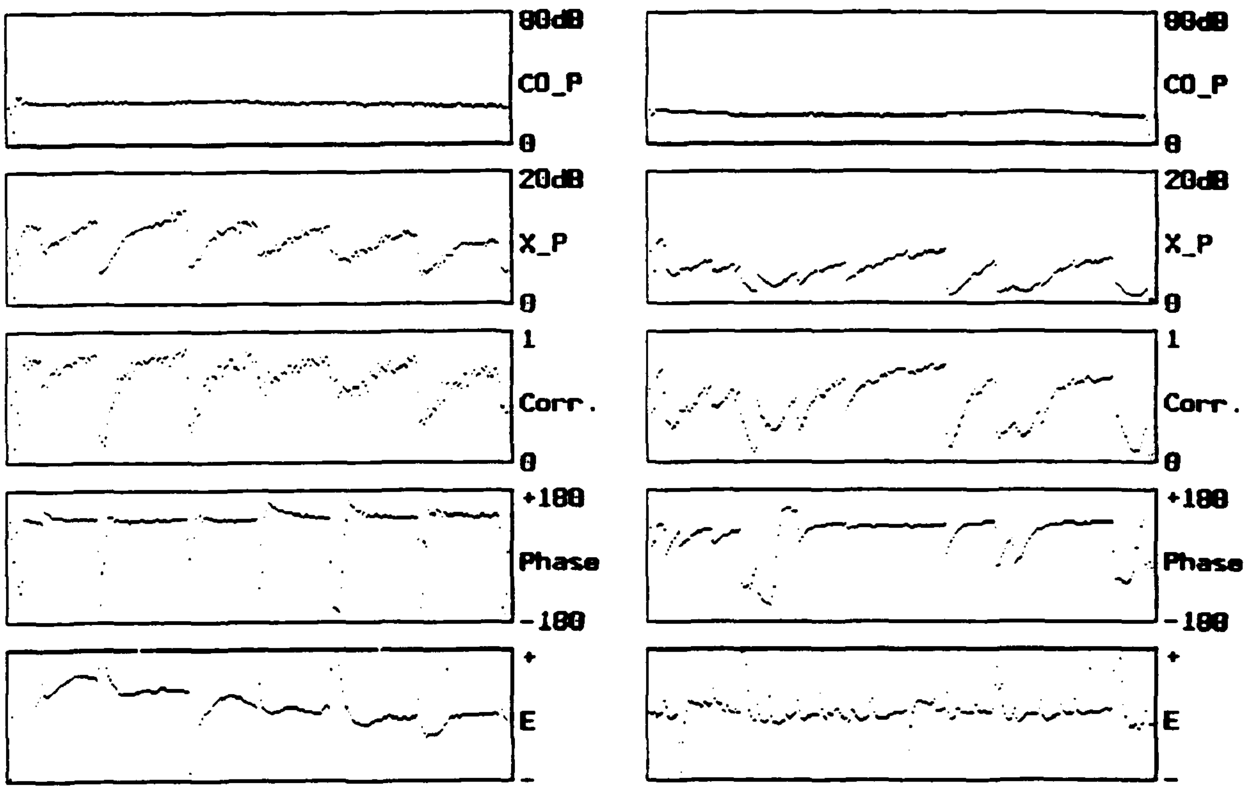

Figure 2. Examples of the time variation of the polarization variables over 5-minute time intervals at a fixed location in two lightning-producing storms. Shown from top to bottom are the co-polar and cross-polar reflectivities, the squared magnitude and phase of the correlation function, and the lightning electric field change. The data are from altitudes of 8.7 km (Figure 2a, left) and 10.4 km (Figure 2b, right).

The correlation measurements have also been used to detect the onset of electrification in several storms, before the first lightning discharge. During the initial stages of storms, and often in later stages as well, the region of strong correlation is observed between about 6 and 8 or 9 km altitude MSL and is co-located with the storm core. This coincides approximately with the altitude of the main negative charge in storms. In one storm, the altitude of the correlation region was observed to decrease as the storm dissipated, down to just above the melting level. In several instances, storms which were decaying and had not produced lightning for several minutes were observed still to have large correlation values within them, and subsequently went on to produce additional discharges. Storms which are not electrified exhibit weak correlations above the 0 °C level.

Although aligned particles themselves will produce cross-polar returns that are correlated with the co-polar returns, a more important effect is that the circularly polarized radiation is progressively depolarized as it propagates through the aligned particle region (Hendry and McCormick, 1976). As the signal is depolarized, returns of a cross-polar sense are produced even from non-depolarizing particles, that are perfectly correlated with the co-polar return.

Depolarization is a major effect in liquid precipitation due to aerodynamic flattening of drops, and provides a means of remotely sensing the rainfall (e.g. Bringi et al., 1991). The depolarizing effect of rain is seen below 4 km in Figure 1, where CDR and $|\rho|^2$ are seen to increase gradually through regions of stronger precipitation and to maintain large values on the far side of the precipitation. The electrical correlation regions exhibit similar features, indicating that they result primarily from propagation depolarization. This also explains the large magnitudes of the correlation. The alternate explanation is that a large fraction of the particles are aligned; while this could happen at the storm top, it would not occur in mixed precipitation regions, such as at mid-levels, where strong correlations are also observed.

The correlation phase ϕ provides a measure of the direction of particle orientation. The phase values shown in Figure 1a indicate that the particles in the upper part of the storm were oriented in an approximately vertical direction. Liquid precipitation is known to be horizontally oriented, and the phase values in the lower part of the storm are correspondingly different. Intermediate phase values are observed at other locations in the storm.

Alignment correlations are observed with linearly polarized transmissions (horizontal and vertical) but are much less pronounced than with circular polarization. This is because minimal or no depolarization occurs when the particles are aligned parallel or perpendicular to the linear radar polarization.

As seen in Figure 2, alignment effects can also be detected from incoherent measurements of the cross-polar power and CDR. This was noted by Hendry and McCormick (1976) and was previously detected with the radar of this study, using linear polarizations (Krehbiel et al., 1991). As can be seen from Figure 1a, aligned particles produce regions of locally enhanced cross-polar returns and depolarization ratios above the 0 °C level. While incoherent observations by themselves could provide indications of electrical alignment, the indications are not as strong and dramatic (or certain) as those of the correlation results.

5. Acknowledgments. This research was supported by the U.S. Air Force Office of Scientific Research under Grant AFOSR-89-0450.

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